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Ore-forming Conditions of the Blagodat Gold Deposit in the Riphean Metamorphic Rocks of the Yenisey Ridge According to Geochemical and Isotopic Data

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Neodymium and strontium isotopic composition and rare earth elements (REE) distribution pattern have been determined in whole rocks and minerals were separated from host metamorphic rocks and disseminated sulfide ores of the Blagodat gold deposit. Isotopic data are given to construct few isochrones that could be reflected an age of main stages of metamorphic and metasomatic alteration in rocks varieties during a successive accumulation of gold in structural traps.
The significant temporal range in the forming of the studied rocks can be interpreted as an evidence of multi-stage tectonic destruction accompanying with trust-folding processes, shear deformations and development of local fracture zones that had place from the Late Riphean to Middle Paleozoic time. According to isotopic data basic ore-forming processes were realized in the relatively narrow interval from 690 to 750 Ma that correspond to a beginning of continental rifting on the western margin of Siberian craton.
Chemistry and trace element distribution are closed for host and auriferous schists and mainly showed differences in the composition initial sedimentary units. The middle negative value εNd (from -14 to -16) and very high positive value εSr (from +570 to +725) are mostly corresponded to that of upper continental crust matter. The role of synchronic granite intrusions in the studied area can be only estimated due to a generation of thermal energy and crustal fluids.

Keywords: Yenisey ridge, metamorphism, Blagodat deposit, genesis, Rb, Sr, Nd, Sm isotopes, gold, isotopic age, geochemistry, Riphean time.

Introduction

The Yenisey ridge is one of oldest ore-bearing province in Siberia where a gold exploration began since the middle of 19-th century. At last time the attention of researches is focused on disseminated

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type deposits that can have a very important significance for the economic development of region. Mostly of ore bodies present by local zones of sulfide mineralization in Precambrian metamorphic formations associated with quartz veins. The typical example of this gold-bearing formation is the Blagodat deposit that was opened about 30 years ago. Firstly it was estimated as a small ore body of quartz-sulfide type. More recent studies have demonstrated a wide spatial distribution of gold in directly metamorphic rocks. Our researches showed that a structure and geochemistry of this object are reflected a very complex history that could present due to multi-stage fold and shear deformations of rocks during few tectonic events (Sazonov et al., 2005)

The gold-bearing mineralization typically show late orogenic emplacement linked to the granitoid magmatism which had significant role in Neoproterozoic structures of the Yenisey ridge. Modern geodynamic conception assumed a development of complete thrust-fold systems on the western margin of Siberian craton caused by subductional and collisional processes accompanying with a mantle plume activity. (Sazonov, 1998; Vernikovsky et al., 2003; Vrublevsky et al., 2003). As a rule, ore deposits are subjects of more thorough research, so the forming of them is a key for understating structural position of rock complexes, their metamorphic recrystallization and metallogeny. Most genetic aspects of gold-bearing mineralization propose to study an age and matter sources of auriferous fluids. In this paper we are discussed these questions on the example of the Blagodat deposit. Our Sm-Nd and Rb-Sr isotopic data as well as chemistry, trace element distribution and REE patterns are assumed a new model of gold accumulation connected with a tectonic evolution of the Middle Riphean Corda Formation units during a significant temporal range. Perhaps this model isn't typical for all disseminated sulfide deposits of the Yenisey ridge, but it can apply to similar mineralized zones in most folded systems of ancient continental margins.

Geological setting of gold deposits in the Yenisey ridge

The Yenisey ridge is a complex Precambrian folded belt located between the Siberian craton and the Western Siberian plate (Fig. 1). The NW-trending structures of the belt combine two segments separated by the ENE-trending Angara Fault which is strike-slip structure. North of Angara Fault, the Yenisey ridge is predominantly composed of Neoproterozoic rocks, comprising the East Angara, Central Angara and Isakov terranes (Vernikovsky et al., 2003). The collision of them accompanying to the widespread trusting and regional metamorphism is corresponded to the Baikalic tectonic stage during the Late Riphean time.

Most of gold deposits are located in the Central Angara terrane. Its internal structure presents by a combination of narrow anticlinorriums and more wide synclinoriums with local domes in the central part where ancient rocks of the Early Proterozoic formations are mainly found. The Central Angara terrane comprises flysch-like and terrigenous-carbonate sediments that were metamorphosed from greenschists to amphibolite facies (Kozlov, Lepezin, 1995). The increasing of temperature of regional metamorphism is directed from greenschists on wings of anticlinoriums to amphibolite grade at their arches. In some cases the spatial transition from the regionally metamorphosed low-pressure (andalusite-sillimanite type) rocks to higher-pressure rocks is marked by a kyanite isograde near largest thrust faults (Likhanov, Reverdatto, 2002).

All these rocks of the Central Angara terrane were intruded by the Tatar-Ayakhta calc-alkaline granites with the age of 760 Ma (Vernikovskaya et al., 2003) and by smaller bodies of the Glushikha

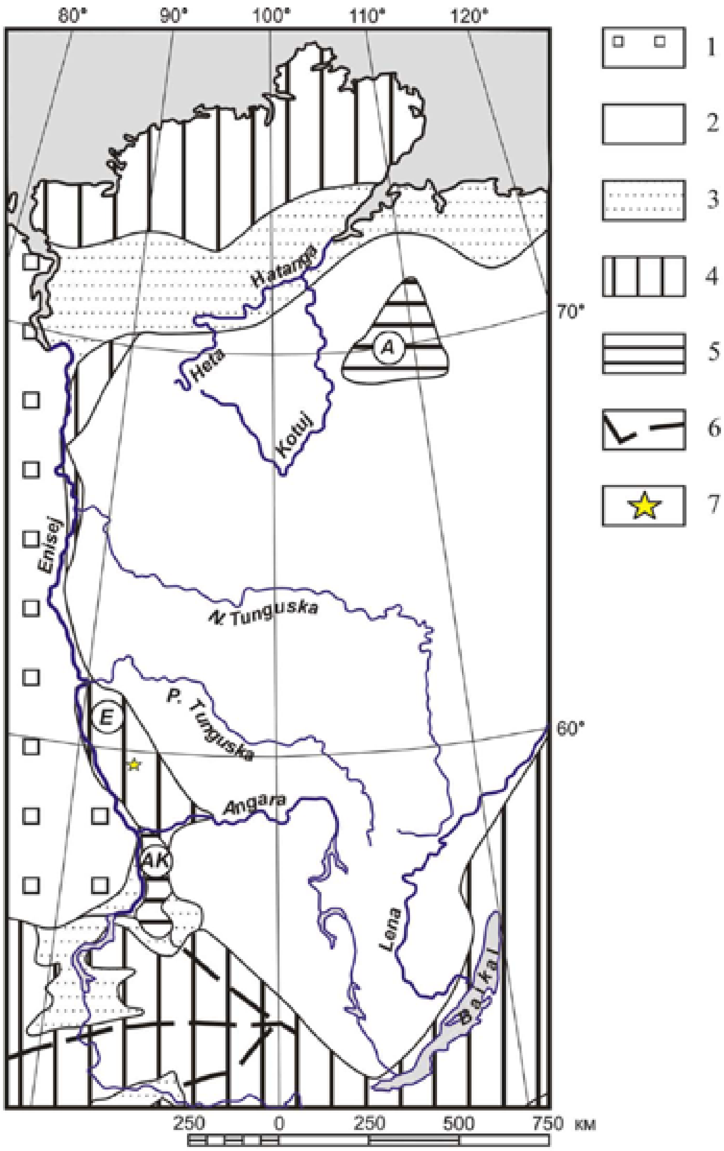


Fig. 1. Tectonic scheme of the Central Siberia: 1 – the Western Siberian plate; 2 – the Siberian craton; 3 – orogenic and postorogenic depressions; 4 – folded areas: E - Northern segment of the the Yenisey ridge; 5 – the Archean blocks: A - the Anabar massif; AK - the Angaro-Kan block; 6 – regional deep fault zones; 7 – location of the Blagodat deposit

leucogranites with the age of 720–750 Ma (Vernikovsky et al., 2003; Vernikovskaya et al., 2002). The Sm-Nd model age (T_{DM}) for this rocks range from 1.6 to 2.2 Ga (Vernikovskaya et al., 2003). As a rule, granitoides are traced along axes of anticlinoriums. Their bodies have a line NW-trended shape. Granitoides of the Tatar-Ayakhta complex are usually characterized by a gradual conversion to country rocks and frequently have relicts of bedding, gneissic structures and nodular textures that assume their syntectonic origin during the Baikalic collision. The Glushikha leucogranite are mainly considered as products of late- or postcollisional magmatism (Vernikovsky et al., 2003). Latest magmatic activity in the region was determined by continental rifting with a development of Early Vendian (640-680 Ma) alkaline basic and ultrabasic small intrusions (Vrublevsky et al., 2003).

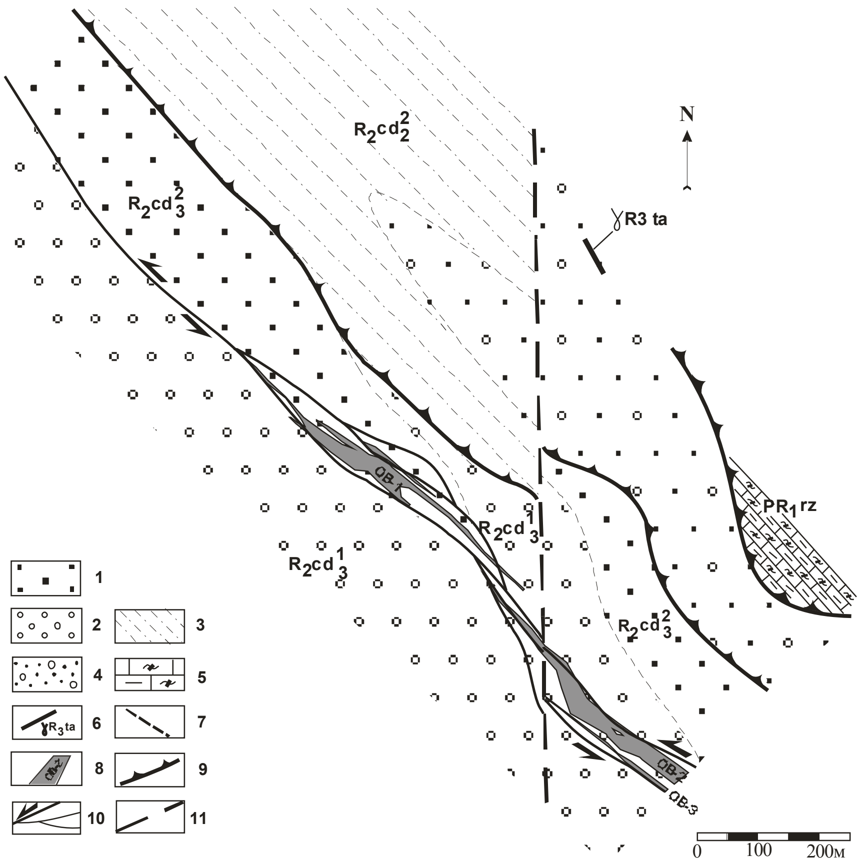


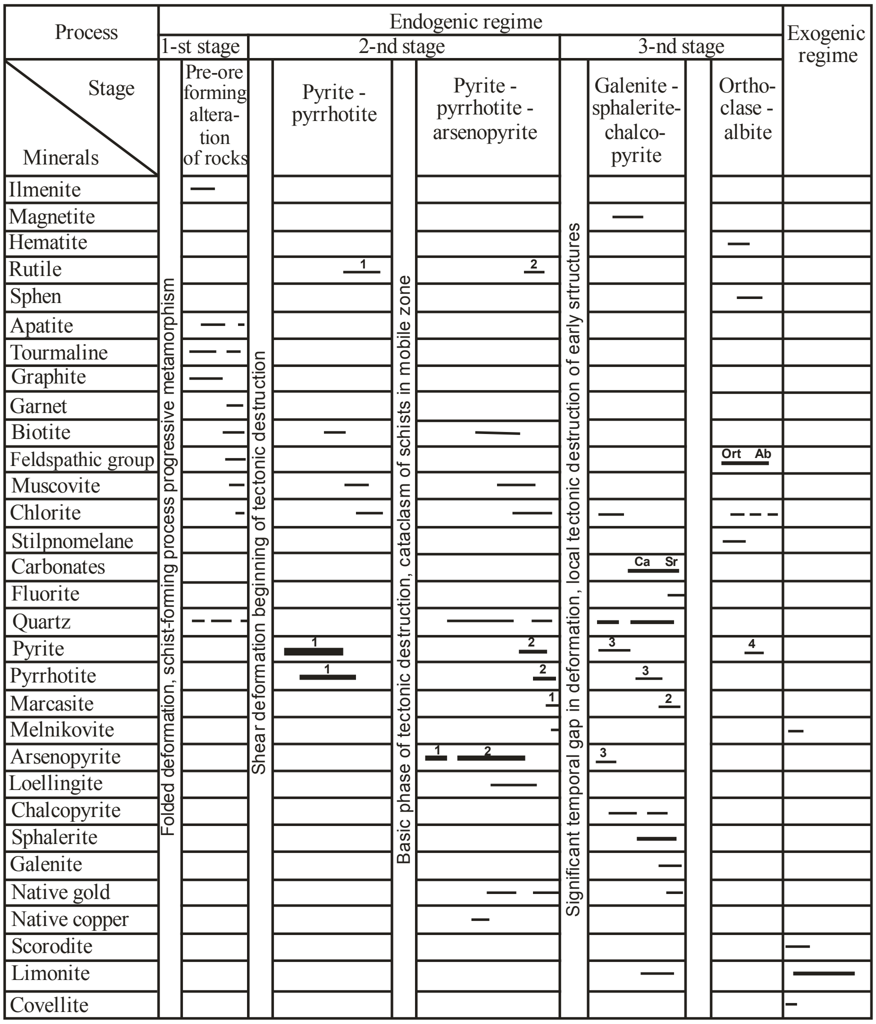
Fig. 2. Geological map of the Blagodat deposit: Upper section of the Corda formation: 1 –quartz-rich and micaceous schists ($R_2cd^2{}_3$), 2 – staurolite-bearing schists ($R_2cd^1{}_3$); Middle section of the Corda formation: 3 – metaarkoses and quartz-rich metasandstones ($R_2cd^2{}_2$); 4 – muscovite-bearing metaalevrolites ($R_2cd^1{}_2$); 5 – calciphyres of the Ryazanov formation (PR_1 rz); 6 – granite dykes of the Tatar-Ayakhta intrusive complex (R_3ta); 7 – stratic boundaries; 8 – ore bodies and their numbers; 9 – thrusts; 10 – shear faults; 11 – normal faults

Gold deposits of region are previously located on facies borders of zonal regional metamorphism, in tectonic metamorphic anomalies complicated by line and brachyaxial folds. Metamorphism and gold mineralization are conditioned by flows of deep high temperature solutions. Gold-sulfide deposits are located in the structures complicating brachyaxial folds, whereas line folds are complicated by quartz-reef deposits.

The background content of gold in metamorphic rocks has a tendency to rise into areas of folding and metamorphism with active participation subcrustal fluids. Nevertheless the transportability of metal in the process of local metamorphism does not accompanied by economical concentrating. Gold deposits are formed in deep fracture zones, where the dynamothermal metamorphism is terminated by the auriferous hydrothermal process. Deep fluid emanations promote granite-forming processes in the low sections of the earth crust and regional metamorphism of folded series. These emanations are powerful source and transport of noble metals for forming of gold deposits in metamorphic series of the Yenisey ridge.

The Blagodat deposit is a new gold-bearing object located in 25 km to the north from the Olympiada gold deposit that is one of largest and famous in Siberia. The gold-bearing sulfide mineralization was

Table 1. Paragenethic scheme of hydrothermal-metasomatic formation of mineral



formed in the upper section of the Corda Middle Riphean Formation rocks of that are represented by staurolite- and garnet-bearing micaceous schists metamorphosed to the epidot-ampholite grade (Fig. 2). Petrographic features of these rocks assume to divide three kinds of lithological units corresponding to staurolite-bearing, micaceous and quartz-rich schists. Their stratigraphical position isn't an obvious, but we consider the following sequence. Staurolite-bearing schists are more spread in the bottom of vertical section, whereas micaceous and quartz-rich schists are located in the upper part of that. More over quartz-rich and arkose metasandstones and muscovite-bearing metaaleurolittes of middle section of the Corda Formation previously metamorphosed in the greenschist grade as well as calciphyres of the Early Proterozoic Ryazanov Formation are located on the eastern flank of the Blagodat deposit.

There are three main stages of deformation in this area. The first stage was defined by trusting and folding of primary sedimentary layers with a local progressive metamorphism and forming of NW-trending thrust-fold system. In the second stage a subparallel shear zone was developed along a syncline hinge in the central part of thrust sheet under conditions of regressive metamorphic regime. This deformation was realized as a NW-trending normal fault completed by strike-slip left-lateral shifting that controlled the gold-bearing sulfide mineralization. The diamond-like shape of main ore bodies suggest their origin as duplex or an echelon of like to "pull-apart" structures where host metamorphic rocks were influenced by sulfur-rich juvenile fluids. The latest deformation continued in the similar dynamic regime and let to a transverse destruction of the deposit by N-trending normal faults. The gold content is very range into ore bodies and reflected a predominant accumulation of metal in local fracture zones within hinges of high order folds. Granite intrusions are rare in this area and mainly present by dikes corresponding to the Tatar-Ayakhta complex.

The gold-bearing mineral paragenesis includes pyrrhotite, pyrite and arsenopyrite in association with quartz. Late smaller fluorite-carbonate veins additionally contain chalcopyrite, sphalerite and galena. The total scheme of temporal sequence of forming for different mineral associations is illustrated by the Table 1. As a rule, highest contents of gold are typical for late stages of metasomatic recrystallization in the endogenic regime.

Samples and analytical procedures

More two hundreds samples (weight ~ 0,2-0,8 kg) from the Blagodat deposit were collected to represent the compositional range of metamorphic rocks and ores. Most of them are fresh, with completely preserved metamorphic and metasomatic mineralogy. Nevertheless weathering crusts were carefully removed before crushing. Major-element concentrations were determined by conventional X-ray fluorescence (XRF) techniques at the United Institute of Geology, Geophysics and Mineralogy of Siberian Branch of Russian Science Academy. Trace element concentrations were measured with neutron activation analytical techniques at the Tomsk Polytechnical University. The chemical composition of main petrographic types and their geochemical features are presented in Table 2.

Only nine samples were selected for isotopic researches. They correspond to host metamorphic rocks, their metasomatically altered sulfide-bearing varieties and fluorite-carbonate-quartz hydrothermal veins. Two samples denoted as 53/254 and 67/51,7 are present host staurolite-bearing schists that collect out of ore bodies. Their composition additionaly includes such typical minerals of progressive metamorphic stage as garnet, biotite, muscovite and quartz without sulfides. The content of gold in this rocks is less 50 ppb. The sample noted as 53/200,5 is corresponded to the garnet-bearing micaceous schist located in the rim of ore body. It is a slightly sulfurized rock with a content of gold about 300 ppb that can explain this variety as a halo of sulfide-mineralized zones. This ore mineral association includes pyrrhotite and pyrite only.

Three samples (36/136, 36/171, 4/169.7) directly collected from ore bodies are present by moderate and more higher sulfurized micaceous schists where the content of gold varies from 500 to 1800 ppb. Their mineralogy is similar to that from rocks of halo, but differs more wide spectrum of ore minerals included chalcopyrite, arsenopyrite and loellingite with rare grains of native cooper and gold. Other samples (No 5/102.8, 5/118.5, 45/145.3) were collected from quartz-carbonate hydrothermal veins that crosscut auriferous reefs. Their mineralogy is also characterized by a presence of fluorite, chalcopyrite, sphalerite and galena. The content of gold in this veins is frequently more high and can rise to few tens ppm.

The Sm- and Sr-isotopic data were received for whole rock samples and some mineral separates such as muscovite, biotite and fluorite. These analyses were performed at the Institute of Precambrian Geology and Geochronology of Russian Science Academy. The Nd- and Sr isotopic composition was

Table 2. Major (in wt %) and trace (in ppm) elements average content in main groups of rocks from the Blagodat deposit

	quartz-rich schists		micaceous schists		staurolite-bearing schists		milonites	
	host	ore	host	ore	host	ore	host	ore
SiO_2	68,19	68,30	60,09	60,13	57,74	57,93	56,88	57,10
TiO_2	0,75	0,80	1,11	1,04	1,03	1,03	1,07	1,09
AL_2O_3	14,24	15,16	17,75	17,58	20,04	20,30	20,40	21,16
Fe_2O_3	6,64	6,88	10,02	10,05	9,89	9,88	9,02	9,05
MnO	0,21	0,08	0,15	0,15	0,20	0,21	0,20	0,19
MgO	0,87	0,99	1,24	1,30	1,32	1,22	1,26	1,18
CaO	0,80	0,32	0,54	0,56	0,49	0,53	0,75	0,35
Na_2O	1,47	1,37	1,51	1,75	1,42	1,36	1,96	1,27
K_2O	3,01	3,08	3,83	3,72	3,77	3,75	3,67	4,43
P_2O_5	0,08	0,05	0,09	0,11	0,13	0,13	0,29	0,10
Ba	0,06	0,06	0,07	0,07	0,08	0,08	0,06	0,07
LOI	3,75	2,90	3,61	3,55	3,90	3,58	4,45	4,01
La	45,55	41,78	57,18	57,17	66,40	64,23	64,50	69,12
Ce	106,51	66,67	123,33	110,78	147,12	130,95	150,93	140,22
Sm	7,07	5,81	7,75	7,69	9,21	8,33	9,09	8,91
Eu	0,18	0,16	0,22	0,25	0,21	0,15	0,14	0,20
Gd	3,55	2,62	3,66	3,54	5,38	4,77	6,53	4,48
Tb	1,05	1,13	1,29	1,11	1,49	1,49	1,64	1,45
Yb	3,48	3,15	3,88	4,13	4,34	3,58	4,14	3,36
Lu	0,46	0,43	0,48	0,56	0,54	0,59	0,46	0,59
U	4,75	9,38	4,03	4,87	5,85	3,97	6,56	6,08
Th	18,04	15,82	24,02	22,02	25,29	25,54	24,14	28,17
As	123	134	664	1038	186	678	487	1318
Au	0,05	1,50	0,13	3,45	0,10	1,93	0,58	3,39

Host – host metamorphic rocks located out of ore bodies; ore – sulfurized varieties of rocks located into ore bodies.

analyzed in static mode on a Finnigan MAT 261 mass spectrometer equipped with variable 8-collector system following standard technique. Element concentrations were measured by the isotope dilution method with addition of ^{149}Sm, ^{150}Nd, ^{84}Sr and ^{85}Rb tracers. The precessions of their values reported hereafter in BCR-1 standard correspond to 95 % confidence level. Nd-isotopic ratios are reported relative to $^{143}Nd/^{144}Nd = 0.511865 \pm 0.000018$ in La Jolla standard on 3 runs. The mean $^{87}Sr/^{86}Sr$ for NBS SRM-987 is 0.710283 ± 0.000021 on 5 runs.

Data regressions have been performed using the Isoplote programm, version 2.0 (Ludwig, 1989) with precessions for $^{143}Nd/^{144}Nd$ are no more ± 0.005 % and the external precession for $^{147}Sm/^{144}Nd$ is ± 0.5 %. Both internal and external precessions for $^{87}Sr/^{86}Sr$ are ± 0.01 % and external precessions for $^{87}Rb/^{86}Sr$ are ± 1.0 %. Nd-isotopic compositions are given in the εNd notation as proposed by DePaolo and Wasserburg (1976) with values calculated using the CHUR parameters of Faure (1986). Sr-isotopic compositions are given in the initial $^{87}Sr/^{86}Sr$ ratio for corresponding age and in the εSr notation with values calculated using the UR parameters of DePaolo (1989).

Results

Major- and trace-element concentrations

Major element chemistry of studied rocks (Table 2) assumes to divide three kinds of them corresponding to follow groups: a) metapelites or high-rank metagraywackes with 57-58 wt % of SiO_2 and about 20 wt % Al_2O_3 (staurolite-bearing schists and their milinotes); b) metaaleurolites or low-rank metagraywackes where the content of SiO_2 is about 60 wt % and content of Al_2O_3 is about 18 wt % (micaceous schists previously); c) arcose metaaleurolites or quartz-rich metasandstones mostly enriched by SiO_2 to 68-70 wt % with a relative deficiency Al_2O_3 that is no more 15 wt % (quartz-rich schists). This chemical features are typical for continental margin sediments that assumes a wide participation of upper crust material in the forming of parental sedimentary sequences. The comparison of compositions of metamorphic rocks and their sulfurized kinds is demonstrated a complete harmony. It is previously confirmed differences in the composition of rocks from middle and upper section of the Corda formation only, but not a variety between host and ore-bearing rocks. The enrichment of K_2O relative to Na_2O in studied rocks could be caused by the silica-potassic metasomatism connected with regional syntectonic deformations or by a specific composition of sources such as potassium-rich granitoides or migmatites from surrounding cratonic blocks.

REE distributions were analyzed in more hundred samples from host and ore bearing series of the Blagodat deposit. Concentrations of these elements from different kinds of rocks are closed between each other so only average contents are presented in Fig. 3. REE patterns of studied schists are differed from that of post-Archean continental shales from the Australian, North American and European regions and the average upper crust (shadow field in Fig. 3) in slightly high level of REE content normalized to chondrite. A presence of negative Eu-anomaly can be regarded as an indicator of protolith corresponding to silica-rich igneous rocks. Indeed, REE pattern for studied schists are mostly similar to that for granitoides from the Yenisey ridge folded area. It could confirm a predominant role of granitic substrates as a weathering source of sediments or a similar geodynamic regime of forming for both metamorphic complexes and syncollisional granitoids. The slight decrease of REE content in the rock row from straulolite-bearing to quartz-rich kinds is probably accompanied with a various amount of REE-poor mineral phase such as quartz.

The geochemistry of other elements is only studied in rocks from the ore-bearing zone of the Blagodat deposit. The concentration coefficient calculated relative to the average content of component in the upper crust ($C_c = C_{ore\ bodies}/C_{clarc}$) is showed a mobility of lithophile and siderophile elements during ore-forming processes. The ore composition ranged according to decreasing of concentration coefficient is represented as next row: As (445), Au (275), W (13.3), Ag (4.3), B (4.1), Pb (2.7), Mo (2.5), Zn (2.0), Ti (1.8), Sn (1.6), Co (1.6), Cr (1.4), V (1.3), Cu (1.2), Nb (1.1) Mn and Ni (0.95), Be (0.89), Ba (0.88). The dominate role for ores belongs to Au and As ($C_c > 100$), as well as the majority of elements is characterized by concentrations closed to clark. The comparison of rock compositions from different parts of sulfurized zones is demonstrated some peculiarities related with the sequence of ore-forming sulfide mineralization. Host metamorphic rocks with ore-less quartzs veins are characterized by higher concentrations of W, Ti, Zn and Co, but lower concentrations of Mn, V and Cu. The pyrite-

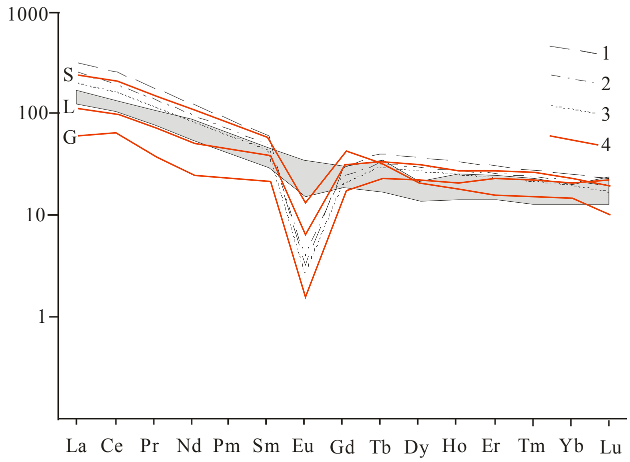


Fig. 3. Chondrite-normalized REE patterns for the average composition of schists from the Blagodat deposit and for granites from the Yenisey Ridge province (Vernikovsky et al., 2002): 1-3 – rocks of the Blagodat deposit (1 – staurolite-bearing schists, 2 – micaceous schists, 3 – quartz-rich schists), 4 – granites of the Yenisey ridge (S – the Strelkovk massif, L – the Lendakh massif, G – Glushikhin massif). The shadow field is corresponded to the average composition of post-Archean Australian sedimentary rocks (after McLennan, 1989), European shale (after Haskin & Haskin, 1966), North American shale composition (after Haskin & Haskin, 1966; Gromet et al., 1984) and average upper crust (after Taylor & McLennan, 1981). Chondrite REE concentrations are after Sun & Donugh (1989)

and pyrhotite-bearing sulfurized rocks from periphery zones of ore bodies are enriched by V, Nb and Mn, B, Cr, Sn, Co accordingly. Arsenopyrite and sphalerite mineralized rocks are distinguished by accumulation of chalcophile elements such as As, Ag, Pb, Cu, Zn, Mo as well as Au, W and Ti. Therefore early sulfide mineralization is described by maximum values of concentration coefficient of siderophile elements (Co, Ti, Mn, Cr) with slightly enrichment of W and Au, while the late auriferous mineralization accompanied with quartz veins is characterized by highest concentration of chalcophile elements (Pb, Cu, Zn, Mo, W) as well as As, Au and Ag.

Sm-Nd and Rb-Sr chronology

The Sm-Nd and Rb-Sr isotopic data for whole rock samples and mineral separates are listed in Table 3. The content of Sm and Nd in studied schists of the Blagodat deposit is demonstrated moderate variations with a maximum of values in muscovite-rich kinds of rocks. Similar or slightly higher level of accumulation for these elements is established in fluorite separates that assumes a metamorphic origin of late quartz-carbonatite hydrothermal veins. Variations of Rb and Sr contents are wider and correspond to a tendency to concentrate a strontium in micaceous schists or in the fluorite of veins as well as rubidium in the biotite. The highest ratio of $^{187}Rb/^{186}Sr$ in biotites from studied schists allow more carefully to remark an isotopic age of main stages during ore-forming sulfurized processes.

In the Sm-Nd evolutionary diagram, data points of bulk samples represented by six different rock types are approximated (MSWD = 0.67) by a regression line with a slope corresponding to an age of 785 ± 45 Ma (Fig. 4). The εNd value for this line is –14.4. The revealed isotopic age can be regarded as a final stage of regional progressive metamorphism that reflects a forming of main mineral assemblage in studied schists. Moreover data points of three fluorite separates from late fluorite-carbonate veins are well approximated (MSWD = 0.058) by regression line with a slope corresponding to an age of

Table 3. Nd and Sr isotopic composition in rock and mineral of the Blagodat deposit

№	Sample	Material	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm 2\sigma$	εNd	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$	$^{87}Sr/^{86}Sr_0$	εSr
							T = 785 Ma					T = 785 Ma	
1.	53/259	Whole rock	7,927	21,82	0,21960	0,512031±18	-14,18	199,1	55,88	10,44509	0,861318±22	0,744235	+579,3
2.	53/259	Muscovite						158,6	117,4	3,93785	0,788236±29	0,744095	+576,5
3.	53/259	Biotite						408,9	14,33	91,07854	1,764851±48	0,743919	+585,5
4.	67/51,7	Whole rock	14,76	41,33	0,21653	0,512001±16	-14,46	166,9	1099,7	0,43959	0,749373±24	0,744445	+581,0
5.	67/51,7	Muscovite						221,8	155,9	4,15048	0,790431±21	0,743907	+573,8
												T = 752 Ma	
6.	53/200,5	Whole rock	6,327	18,61	0,20616	0,511937±15	-14,66	114,1	47,08	7,04436	0,819408±31	0,743782	+574,4
7.	53/200,5	Muscovite						227,3	148,2	4,47280	0,791380±25	0,743362	+567,2
8.	53/200,5	Biotite						722,5	12,11	211,61729	3,018875±125	0,747033	+724,2
												T = 698 Ma	
9.	4/169,7	Whole rock	7,236	37,21	0,11754	0,511494±12	-14,31	108,0	68,38	4,61193	0,795085±32	0,748966	+643,7
10.	4/169,7	Muscovite						229,0	136,5	4,89752	0,798163±39	0,749188	+646,8
11.	36/171	Whole rock	13,81	47,50	0,17632	0,511802±14	-14,27	153,8	80,26	5,59116	0,805371±27	0,749459	+650,8
12.	36/171	Muscovite						188,3	101,5	5,41847	0,803874±33	0,749689	+653,9
13.	36/136	Whole rock	6,741	24,86	0,16393	0,511705±17	-14,20	52,79	133,5	2,54413	0,772864±19	0,747522	+621,7
14.	36/136	Muscovite						181,6	142,4	3,71907	0,785582±36	0,748181	+635,5
15.	36/136	Biotite						341,4	38,19	26,64109	1,013550±47	0,748537	+617,8
							T = 368Ma					T = 368Ma	
16.	5/102,8	Fluorite	45,76	85,23	0,324461	0,512095±11	-16,60	0,755	110,7	0,01974	0,748624±25	0,748521	+631,3
17.	5/118,5	Fluorite	9,919	47,04	0,12747	0,511622±12	-16,60	1,425	59,35	0,06947	0,749017±22	0,748656	+633,3
18.	45/145,3	Fluorite	5,840	33,42	0,10564	0,511565±12	-16,68	102,8	274,0	1,08541	0,754212±26	0,748568	+632,0

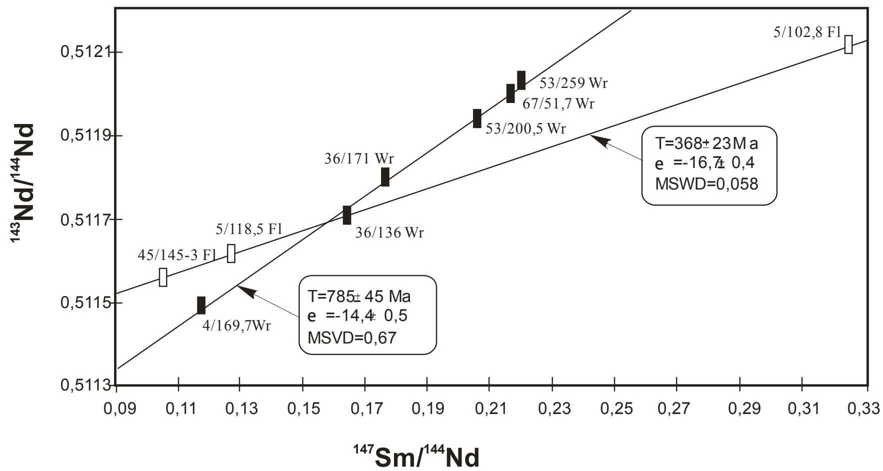


Fig. 4. $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ plot for bulk samples of schists and fluorite separates from quartz-carbonate veins. Numbers of data points are corresponded to table 3

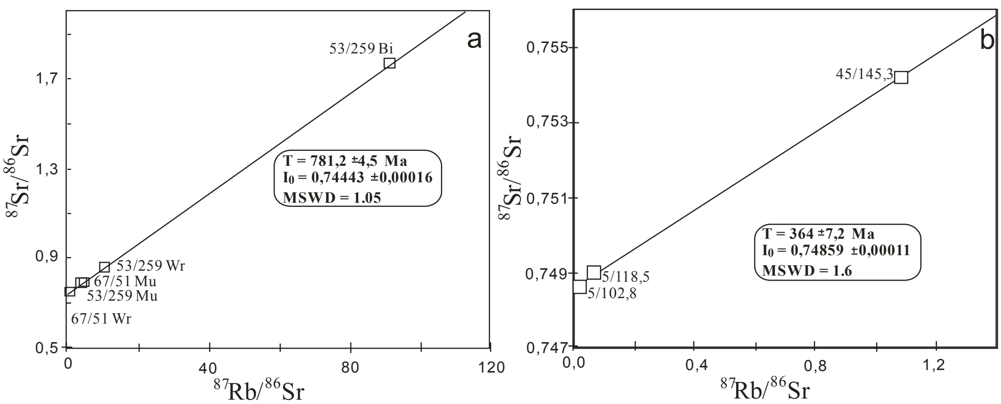


Fig.5. Rb-Sr isochron plot of whole rock samples and mica separates from host staurolite-bearing schists (A) and from the fluorite separates of quartz-carbonate veins (B) giving a temporal range of Blagodat deposit forming

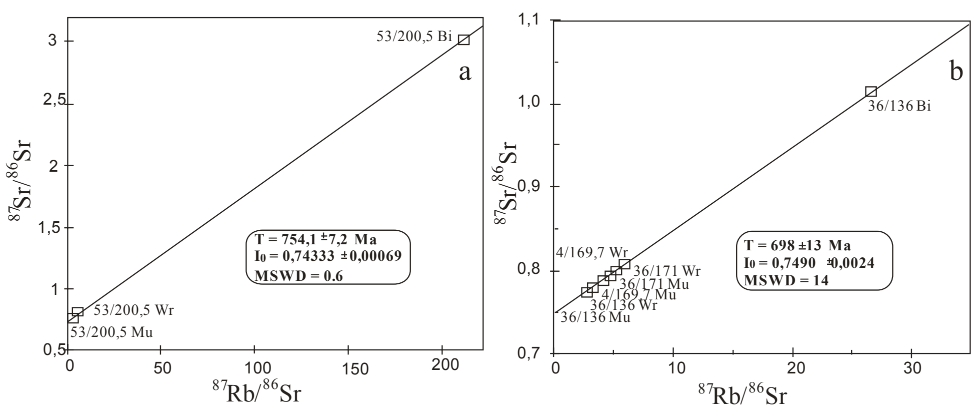


Fig. 6. $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ plot for slightly sulfurized micaceous schists (A) and auriferous metamorphic rock from the ore bodies (B) showing a probable duration of shear deformations in the Blagodat deposit

368 ± 23 Ma (Fig. 4) with the εNd value of –16.7. It is interesting to mark that one data point of whole ore-bearing schist denoted 36/136 is deviated from main regressive line to that of fluorite separates. The careful petrographic study of this sample is defined a presence of fine quartz-carbonate veins with chalcopyrite and sphalerite that genetically connect with a fluorite-bearing mineralization. The significant temporal gap showed in the Sm-Nd geochronology assumes a very long history of mineralization in the Blagodat deposit. In this case we must to agree with only two main stages during of which could be realized a redistribution of rare earth elements.

Sm-Nd isotopic ages of regional metamorphism and fluorite-bearing mineralization are confirmed by Rb-Sr isotopic data. The slope regression line calculated for three data points of host spotted staurolite denoted 53/259 (whole rock, muscovite and biotite) is corresponded to the isochron age 785 ± 6.9 Ma (MSWD = 0.043). A Rb-Sr isochon plot constructed on five data points including additionally a bulk sample and muscovite mineral separate from the host micaceous schists (No 67/51.7) is indicated similar age of 781 ± 4.5 Ma at MSWD = 1.05 and $^{87}Sr/^{86}Sr_0$ = 0.74449 ± 0.00016 (Fig. 5 A). The data points of fluorite separates define a liner regression with an age of 364 ± 7.2 Ma at $^{87}Sr/^{86}Sr_0$ = 0.74859 ± 0.00011 and MSWD = 1.6 (Fig. 5 B). This established geochronologic boundaries are reflected a mostly full temporal range of metamorphic and metasomatic processes for a forming of gold-bearing sulfide mineralization in the Blagodat deposit.

The distribution of Sr isotopes in sulfurized varieties of schists have a more important significance for a dating of ore-forming stages related with shear ductile deformations in strike-slip fault zones. The biotite is a main indicator of alkaline metasomatism during these tectonic events, because it concentrates a higher content of rubidium. An isochron on a whole rock, muscovite and biotite mineral separates from the slightly sulfurized micaceous schist denoted 53/200.5 shows an age of 754 ± 7.2 Ma at initial $^{87}Sr/^{86}Sr$ = 0.74333 ± 0.00069 and MSWD = 0.6 (Fig. 6 A). This boundary can be regarded as a beginning of ore-forming processes in shear zones. The slope of regression line calculated for seven data points of auriferous whole rocks and their mineral separates (muscovite and biotite) ore bodies is corresponded to an age of 698 ±13 Ma at initial $^{87}Sr/^{86}Sr$ = 0.7490 ± 0.0024 (Fig. 6 B). This errorchron (MSWD = 13) is mostly defined by one data point of the biotite mineral separate whereas the regression line on six other data points (composition of whole rocks and muscovite separates) is an enough correct isochron (MSWD = 1.3) with an age of 752 ± 10 Ma and is similar to that for sample denoted 53/200.5. The observed discrepancy can be explained by kinetic peculiarities of exchange reactions between rock-forming minerals and ore-forming fluids (Tishin ea al., 2005). The biotite as a more mobile crystalline system is firstly reacted to metasomatic alternation of rocks and reflected a new balance of Sr isotopes. Therefore we suggest to assume an age of 698 Ma as that of basic or late metasomatic stage accompanied with ductile deformations in ore-bearing shear zones.

Nd and Sr isotopic composition

Values of εNd calculated for whole rock samples of schists (T = 785 Ma) range in very narrow interval from -14.2 to - 14.7 whereas those for fluorite separate (T = 368 Ma) are more negative from -16.6 to -16.7 (Table 3). Moreover studied rocks and their minerals are characterized by very high values of initial $^{87}Sr/^{86}Sr$ (more 0.7439) and εSr (more +570) calculated to the corresponding age for different stages of metamorphic and metasomatic processes. Such isotopic parameters previously assumed a upper crust source for host and ore-bearing rocks of the Blagodat deposit. A tendency of increasing

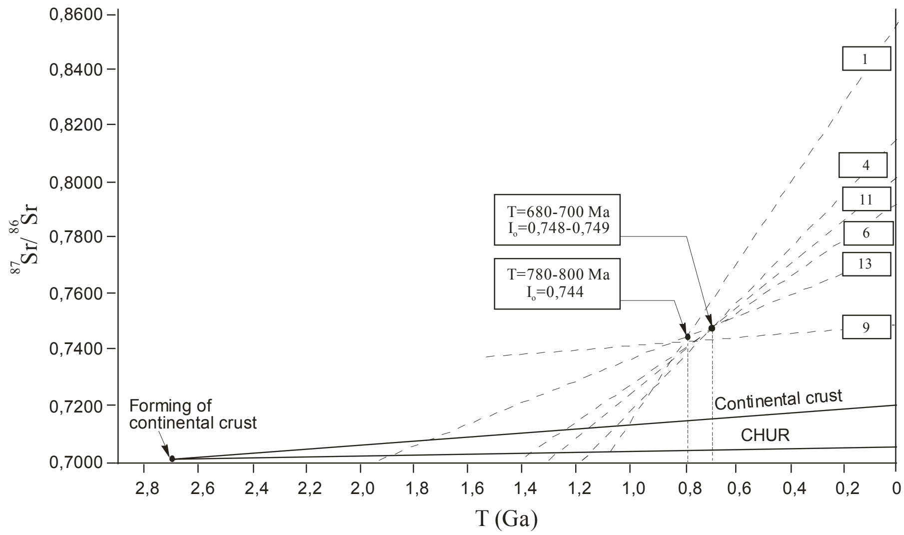


Fig. 7. Evolution of $^{87}Sr/^{86}Sr$ ratio in whole rock samples from the Blagodat deposit (numbers of samples from 1 to 18 corresponded to the table 3) demonstrated Sr model ages of rocks relative to the average composition of upper crust. Numbers of samples from 1 to 18 corresponded to the table 3

crustal component in the source was seen for rocks transformed during subsequent tectonic events. Lower values of εNd in fluorite samples from late quartz veins correspond to this scenario.

Sm/Nd model age calculation using a primary mantle model (T_{CHUR}) on the whole rock mostly range from 1.8- to 2.3 Ga and less to 4.3 Ga that may by interpreted as the age of parental magmatic rocks for clastic sediments. The model age calculated from Sr isotopic composition of upper continental crust (Fig.7) is younger (1.0 – 1.75 Ga) and can be a marker of early exchange reactions related to sedimentation or initial greenschist grade metamorphic processes. Nevertheless a tendency of increase for model age values is distinguished in the row from host schists to ore-bearing rocks of the Blagodat deposit. It is probably connected with an activation of fluids from deep-seating and more ancient formations that be made up a continental crust of the Yenisey ridge fold system.

Discussion

The origin of gold deposit in the metamorphic units is widely discussed during last fifty years (Li and Shokhina, 1974; Boyle, 1979; Kerrich and Fryer, 1981; Anoshin et al., 1982; Groves et al., 1988; Groves and Foster, 1986; Sazonov, 1998; Davis et al., 2002 and other). Many authors show a relationship between ore-producing processes and multi-stage deformations of metamorphic rocks with a participation of basic and granitoid intrusions and hydrothermal fluids during accretional and collisional events on the continental margins of ancient cratons (Kerrich and Wyman, 1990; Nesbitt, 1996; Golding. et al., 1990; Ropchan et al., 2002). The similar geodynamic regime is assumed for the forming of Neoproterozoic structures in the Yenisey ridge too (Vernikovsky et. al, 2003). In this paper we want mainly to consider two important aspects of ore genesis such as temporal duration of gold-forming processes and matter sources of auriferous solutions.

The age of gold-bearing mineralization in the studied region was usually estimated to the Late Riphean time (about 850 Ma) on the base of the K-Ar dating for sulfide ores from the Olympiada deposit (Zvyagina, 1989). Results of our isotopic researches assume to distinguish a more significant temporal range for the accumulation of sulfides and gold in metamorphic units of the Corda Formation. We regard that a segregation of metals was caused by allochemical metamorphism, late metasomatic alteration and hydrothermal processes during few tectonic cycles. Narrow single-line zone of biotite, garnet, staurolite are formed during the progressive regional metamorphism accompanying with trusting, folding, recrystllization and forming of early sulfide mineralization in local extensional structures, perhaps, into hinges of higher order folds. The timing of this process can be correlated with an age of host metamorphic rocks on the Blagodat deposit corresponding of 780-790 Ma (data from Sm-Nd and Rb-Sr composition of host staurolite-bearing schists). The accumulation of gold in these rocks couldn't achieve to economical conditions, but must to provide some rising of gold content in local parts of the Corda Formation. This supposition is based on the enough high content of gold in host rocks of the Blagodat deposit (20-40 ppb) that is more in 3-5 times relative to a clarc of this metal in Earth crust and crystalline schales (Crocket, 1996).

The second stage of gold accumulation began realized during a regressive metamorphism connected with renewal dislocation of shear type that was slightly transverse to the linearity of initial tectonic structures. The combination of strike-slip and normal fault shifting allowed forming of local fracture zones and transporting juvenile fluids from dipper seated metamorphic units. The result of this alteration have been a forming of disseminated sulfide mineralization (pyrrhotite and pyrite) on rims of main ore bodies in the Blagodat deposit. The dating of beginning for gold-producing metasomatic processes into shear sulfured zones could be corresponded to the Rb-Sr isotopic age of low-sulfurized micaceous schists (sample 53/200.5) located on the boundary of northern ore body (OB-1 in Fig. 3). The following development of strike-slip fault dislocations must to provide a remobilization of gold and its segregation in structural traps that demonstrate as main ore bodies and local ore shoots. The mineral paragenesis of this structure includes wider spectrum of sulfides such as a arsenopyrite and chalcopyrite that demonstrate a rising role of hydrothermal fluids. We assume that this process may be correlated with a forming of sulfide-rich mineral assemblage in auriferous schists of main ore bodies. The Rb-Sr isochron for mostly sulfurized schists are corresponded to age of 690-700 Ma that could be defined as basic or latest stages of shear deformations in the transverse strike-slip fault.

The final stage of gold accumulation was obviously connected with additional tectonic activity in the Paleozoic time when only brittle deformations could be realized in the consolidated substrate of the Corda metamorphic units accompanying with the calc-alkaline metasomatic alteration of rocks. Fluorite-carbonate veins with chalcopyrite, sphalerite and galena are main indicators of these tectonic and metamorphic events. We regard that the Sm-Nd and Rb-Sr isotopic dating of fluorite separates (360-370 Ma) are mostly corresponded to this stage.

Thus the total temporal duration of the Blagodat deposit forming could be extended from the Late Riphean (progressive metamorphism, thrusting and folding of host rock units with an age of 780-790 Ma) to the Late Paleozoic (only brittle deformations and forming of local fracture zones with an age of 360-370 Ma). Nevertheless we regard that main ore-forming processes were defined to relatively narrow temporal interval corresponding to 690-760 Ma. This chronological range is mostly correlated with a forming of the Tatar-Ayakhta and Glushikha granite intrusions (720-760 Ma). Their origin is connected with a collision of the Central Angara terrane with the Siberian craton (Vernikovskaya et. al, 2003). Moreover the chronological boundary of 690-700 Ma corresponding to the forming of mostly

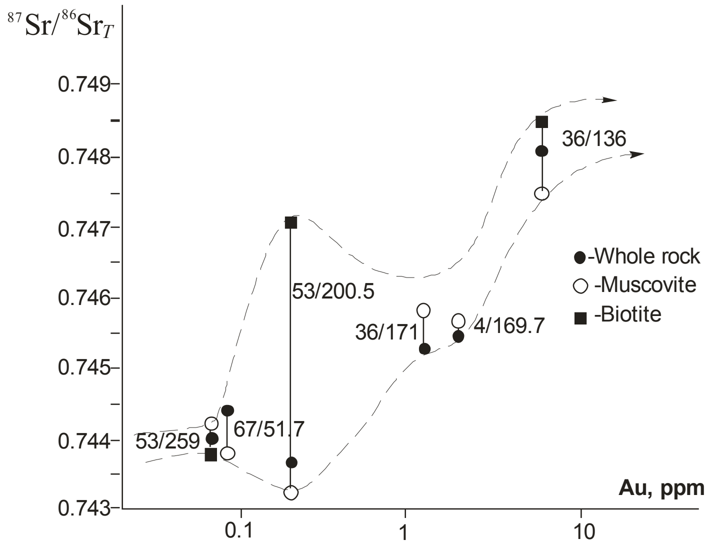


Fig.8. Relationship between values of initial $^{87}Sr/^{86}Sr$ ratio and content of Au (ppm)

auriferous schists in shear zones can be interpreted as a transition to the postcollisional riftogenic regime indicator of which was an alkaline and carbonatite-bearing magmatism in the region with ah age 640-680 Ma (Vrublevsky et al., 2003).

The conformity of isotopic ages for granitoid magmatism and auriferous sulfide mineralization is a considerable to show a genetic relationship between these processes. Same authors regard to assume an aditional role of mantle plumes for the forming of gold deposits in the Yenisey province (Anoshin et al., 1982; Sazonov, 1998). In any case the mater source of host metamorphic rocks and auriferous hydrothermal fluids in gold deposits of the studied region is open now, although it is very important for an interpretation of their genesis. Chemistry of schists as well as their trace element compositions are similar to that of continental terrigenous sediments (sands, aulerolites and shales), whereas REE-patterns are mostly common for silica-rich magmatic rocks. It assumes that main products of clastic or chemical weathering for primary sedimentary units of the Corda Formation could be the Archean and Early Proterozoic granitic or migmatitic complexes from the western margin of Siberian craton. The calculation of model Sm-Nd age relative to the chondrite uniform reservoir (CHUR) in whole rock samples of studied rocks is confirmed this scenario.

The origin of mater sources for gold-bearing metamorphic units from the Blagodat deposit is more correctly estimated by initial Nd- and Sr- isotopic ratios. Values of εNd_T and εSr_T calculated on the determined isochron age for different stages of mineralization are corresponding to parameters of upper continental crust. Middle negative values of εNd_T ranging from –16 to –14 can be correlated with that of enriched mantle reservoir of EM-II type, but they are usually less to this characteristics of syncollisional granites (values of εNd_T are about –10) from the Tatar-Ayakhta complex (Vernikovsky et al., 2003). Very high positive values of εSr_T ranging from +570 to +725 can be only interpreted as a source of upper continental crust component (Bickle et al., 1989). Moreover the sequence of gold accumulation is accompanied with a tendency to rise a role of crust component that illustrate by a direct correlation between gold contents and initial $^{87}Sr/^{86}Sr$ ratios in studied metamorphic rocks (Fig. 8). The decreasing of εNd_T in late fluorite separates is also confirmed this conclusion.

We regards that a source of gold was metamorphic rocks of the Corda formation. Granitic intrusions had an indirect influence over the forming of the Blagodat deposit, despite on the widespread location of them in the frame of studied object. Our isotopic data show that these magmatic rocks could be only a source of thermal energy and hydrothermal solutions. Rb-Sr model ages calculated relative to the middle composition of upper crust (Fig. 7) are demonstrated a successive drawing of fluids from more ancient metamorphic complexes into ore-forming processes.

Conclusion

Our geochemical and isotopic data allow presenting a new model of gold segregation in metamorphic units of the Yenisey ridge province. On the example of the Blagodat deposit the following temporal sequence of gold-produced tectonic and metasomatic transformation is assumed:

a) T = 1200 – 1000 Ma – the sedimentation and early greenschist grade metamorphism of the Corda Formation rocks;
b) T = 800 – 780 Ma – the trust-folded deformation of the primary horizontally layered units, their progressive metamorphism to the amphibolite grade and initial accumulation of gold in local structural traps;
c) T = 760 – 750 Ma – the shear deformation and beginning of sulfidization processes in metamorphic units with a forming of initial disseminated pyrrhotite-pyrite assemblage;
d) T = 700 – 690 Ma – the main or late stage of metasomatic transformation of metamorphic rocks in ore bodies with pyrite-pyrrhotite-arsenopyrite mineralization;
e) T = 370 – 360 Ma – the final tectonic destruction of the Blagodat deposit and forming of fluorite-bearing veins with chalcopyrite-sphalerite-galena paragenesis.

On the base of Sm- and Sr- isotopic data we regard to distinguish only mater sources of upper continental crust for forming of gold-bearing sulfide mineralization in the Blagodat deposit. Most of granitic and alkaline intrusions synchronized to the age of gold-produced processes could be only promoted to the high thermal recrystallization and metasomatic alteration of the Corda Formation rocks which were a main source of gold.

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